NASA CPAS Drogue Textile Riser Feasibility Study

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Steel cable was chosen for the lower end of the drogue and main parachute risers on NASA's Orion Multi Purpose Crew Vehicle Parachute Assembly System (CPAS) to protect the risers from extreme temperatures and abrasion should they contact the crew module during deployment, as was done for Apollo. Due to the weight and deployment complexity inherent in steel, there was significant interest in the possibility of substituting textile for steel for the drogue and main parachute risers. However, textile risers could be damaged when subjected to high temperature and abrasion. Investigations were consequently performed by a subset of the authors to determine whether sacrificial, non-load-bearing textile riser covers could be developed to mitigate the thermal and abrasion concerns. Multiple material combinations were tested, resulting in a cover design capable of protecting the riser against severe riser/crew module contact interactions. A feasibility study was then conducted to evaluate the performance of the textile drogue riser cover in relevant abrasive environments. This paper describes the testing performed and documents the results of this feasibility study.

I. Introduction

THE drogue and main parachute risers for the NASA Orion Multi Purpose Crew Vehicle Parachute Assembly System (CPAS) must be protected from extreme thermal and abrasion conditions encountered upon contact with the crew module during parachute deployment and operation. Steel cable was selected as the baseline material for the lower end of the droge and main risers in part because of its successful performance during the Apollo program. Advances in textile materials made during the past 30 years, however, have prompted investigations into the feasibility of replacing the protected steel riser with a protected textile riser. Advanced textiles have numerous benefits over steel, including lower weight, increased flexibility, higher stowage efficiency, the elimination of stored energy during stowage, and the elimination of a possible thermal bridge between the crew module's Forward Bay Cover and the parachute assembly. A previous investigation [1] evaluated several candidate materials and designs, resulting in a textile protective cover able to completely protect the textile riser from severe riser/crew module contact interactions. This feasibility study was therefore a long-awaited opportunity to conduct a direct comparison between steel and textile risers in a variety of contact environments relevant to the flight configuration.

II. Approach

The objective of this work was to determine and compare the strength knockdown of steel and textile risers resulting from a variety of equivalent abrasive loading conditions derived from [2] and shown in Table 1. Two of these conditions were selected to simulate contact with the crew module at the drogue fair lead and possible contact with

Table 1. Abrasion conditions.

Flight Analogue	**Drogue Fair Lead**	**LAS R&R (min)**	**LAS R&R (nom)***	**LAS R&R (max)**
Edge Material	Steel	Steel	Steel	Steel
Edge Radius (in)	5/8	3/8	1/4	1/8
Normal Force (lb)**	42,000	17,562	17,562	17,562
Bend Angle (deg)	90	60	60	60
Abrasion Distance (in)	60	12	12	12

* Not tested due to limited materials
** From flight peak opening loads

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the launch abort system retention and release (LAS R&R) bracket, respectively. The two remaining conditions simulated loading and bend angles equivalent to the LAS R&R bracket, with oversize and undersize edge radii of 3/8 and 1/8 inches, respectively. Contact with the LAS R&R is predicted to be momentary, whereas contact with the fair lead will be potentially sustained periodic until the drogues are cut away [2].

A. Previous Testing

Previous testing [1] performed at the Naval Air Warfare Center, Weapons Division (NAWCWD), involved testing the effect of thermal and abrasive loading between a representative CPAS Kevlar® riser and a representative contact surface with a 1/4-inch radius. Evaluation of a thermal and abrasive load involved heating the contact surface to the relevant temperature, placing it in loaded contact with the riser, and inducing relative motion. The riser samples were then inspected for damage and loaded to failure to determine the resulting knockdown factor. Protective sleeves were fabricated to reduce the damage to the riser, with the final design demonstrating significant success in reducing the effect of thermal loading and abrasive motion through the use of insulating layers and a rolling sleeve. Fortunately the temperature extremes that were required at the time of these tests had been reduced as the design of Orion matured, allowing for modifications to the sleeve design to reduce weight and bulk.

B. Preliminary Testing at China Lake

A similar approach was taken to evaluate the new candidate cover designs in preparation for full-scale riser abrasion testing. Only one of the abrasion conditions could be evaluated due to time constraints. The contact pressures for each abrasion condition were therefore calculated based on the maximum normal force expected during flight and the total contact area resulting from the edge radius. The condition with the largest contact pressure was selected to drive the design.

Several protective sleeves were designed and fabricated based on previous testing. The design was incrementally modified between abrasion tests to optimize its ability to protect against abrasive damage.

During testing, the edge radius was placed in loaded contact with the protective sleeve on the riser. The contact force was approximately equivalent to the maximum normal force expected during flight. The fixture was then rotated to produce relative motion between the riser and contact surface. The abrasive motion was repeated until the desired total contact distance was reached. The riser was then removed, inspected for damage, and then loaded to failure to determine the resulting knockdown factor. Each protective sleeve was evaluated based on its ability to protect the riser against the abrasive motion and preserve the strength of the riser. The most successful design was selected for more flight-like testing at NASA Johnson Space Center (JSC).

C. Full-Scale Riser Abrasion Testing at NASA Johnson

Full-length protective sleeve samples were tested at the Structural Test Lab of JSC. The riser samples were prepared by Airborne Systems. The protective sleeves were fabricated and installed on-site by China Lake and Airborne Systems personnel.

Each test was configured to simulate in-flight conditions equivalent to or beyond a very severe case. For example, the 1/8-inch radius edge is smaller than any expected contact surface. Additionally, in some cases the protective sleeve was intentionally twisted about the riser lines to limit the rolling motion of the sleeve and increase contact abrasion.

Tests were conducted according to the abrasion conditions listed in Table 1. Primary tests were completed ahead of schedule and additional tests were conducted to further evaluate the capabilities of the protective sleeve.

D. Tensile Testing

Each loop of Kevlar in each riser sample was loaded to failure to determine the overall knockdown factor for a given test configuration. The knockdown analysis compared the different holding methods used during abrasion and ultimate strength trestimg.

E. Assumptions

Testing assumed the following:

1) Knockdown effects related to temperature are independent of abrasion environment.
2) Thermal effects are negligible. The estimated temperature of the contact surface [2] is less than 400ºF, which is below the threshold for Kevlar deterioration [3]. All tests were therefore conducted at room temperature.
3) Continuous contact is conservative. Abrasive contact is more likely to be incidental. All tests were therefore conducted with continuous abrasive contact.

4) Flight contact between the riser and the LAS R&R bracket will allow for rotation of the protective cover. Simulated contact partially restricted rotation of the protective cover, which is more severe than flight contact.

III. Preliminary Testing at China Lake

A. Test Materials

1. Drogue Textile Riser Sample

Photo 1. Kevlar® riser sample with protective cover.

The drogue riser samples were designed and fabricated by Airborne Systems. Each riser sample was composed of 12 loops of 5000-lb specified Kevlar® cord. An example riser sample with a protective sleeve is shown on Photo 1. The blue tape shown identify individual riser loops to aid in test setup and help avoid twisted lines. The loop ends were nested to minimize the pin length, with odd-numbered ends nested on the left end and even-numbered loops nested on the right end of each sample to maintain consistent loop length.

2. Contact Edge

The contact edge with the greatest pressure was determined by the normal load and contact area. The width of the contact area was defined as the riser dimension parallel to the bend axis and was assumed to be approximately equivalent for each condition. The length of the contact area was calculated as the bend angle in radians multiplied by the edge radius. The lengths of the largest and smallest contact areas were therefore calculated to be π/3 x 5/8 inches = 0.6545 inches and π/3 x 1/8 inches = 0.1309 inches, respectively. The contact pressure was then calculated to be 42,000 lb / 0.6545 in = 64,170 lb/in and 17,562 lb / .1309 = 134,200 lb/in, respectively. The smaller contact radius was therefore selected for initial testing. The target contact load used during testing was increased to 17,600 lbs to ensure the desired normal force was reached.

The contact edge was incorporated into the edge of a cylindrical tube. Supports were then attached to the contact edge (Figure 2), which were in turn attached to the turntable of the test assembly (Figure 3).

Figure 2. CAD model of edge radius fixture with turn-table attachments.

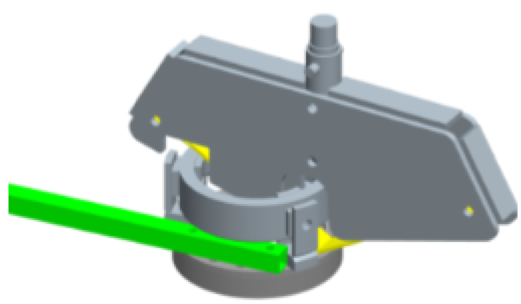

Figure 3. CAD model of edge radius fixture installed on turn-table with attached rotating bar and riser fixture.

The available abrasion distance was constrained by the edge radius fixture attachments shown on Figure 2 and was measured to have an arc length of approximately nine inches. Subtracting the riser width of about two inches resulted in a total traversable arc length of about six inches, which was approximately half of the desired total length, requiring two passes to achieve the desired total abrasion length.

3. Textile Protective Cover

Cover materials were identified based on properties demonstrated in [1]. In general, each sleeve was composed of an inner Kevlar sleeve next to the riser lines, a middle sleeve of Teflon for lubrication, and an outer Kevlar sleeve. This composite sleeve was designed to minimize friction between the inner and outer Kevlar sleeves, thus allowing the outer Kevlar sleeve to “roll” about the riser instead of sliding against the contact edge. The various materials selected for evaluation are shown in Table 2.

Table 2. Cover materials.

Material	Type	Description	Specification	Manufacturer	Part No.	Sleeve	Role
Kevlar® 29	Tube	10,000 lb minimum break strength	None	Synthetic Textiles, Inc	64K10000	Inner/Outer	Abrasion resistance
Kevlar®	Cloth	10-oz plain weave	UNK	UNK	UNK	Inner/Outer	Abrasion resistance
Teflon	Cloth	Plain weave, natural	PAT No 47927	Stern & Stern Lot 5287 WR SP-10-96	T-8-42	Middle	Lubrication
Spectra	Cloth	215 denier, 3.1-oz, plain weave, natural	Style 884-3	Guardian Ship order 421-3916	CRM 04154	Inner/Outer	Abrasion resistance

UNK Unknown

The one-inch lay-flat-width, tubular braid, woven Kevlar® sleeve with 10,000 lb minimum break strength manufactured by Synthetic Textiles, Inc. as model number 64K10000 was found to be very effective. An example is shown on Photo 2.

Photo 2. Tubular Kevlar® outer Kevlar sleeve.

B. Test Setup

All abrasion tests were performed using the same Instron 8800 used in [1], which has a maximum load rating of 56,200 lbs. Additionally, the test series was designed to re-use several existing test fixture components used during previous testing to save fabrication time. A computer aided design (CAD) model image of the test fixture is shown on Figure 4. Photos of the actual test setup are shown on Photo 3, Photo 4, and Photo 5.

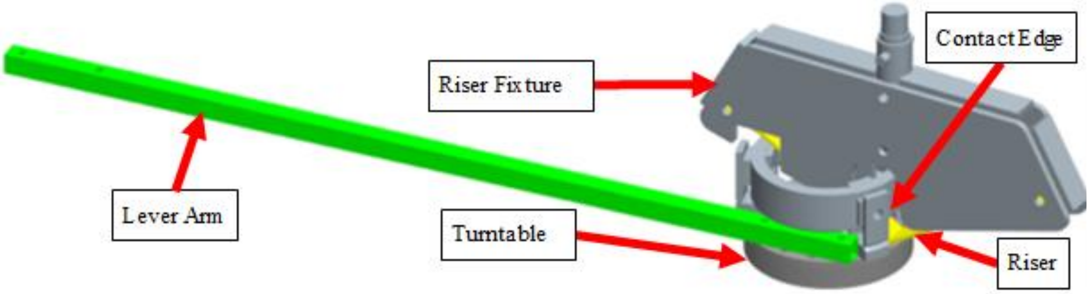

Figure 4. CAD model of fixture.

Photo 3. Test fixture with protected riser and contact edge.

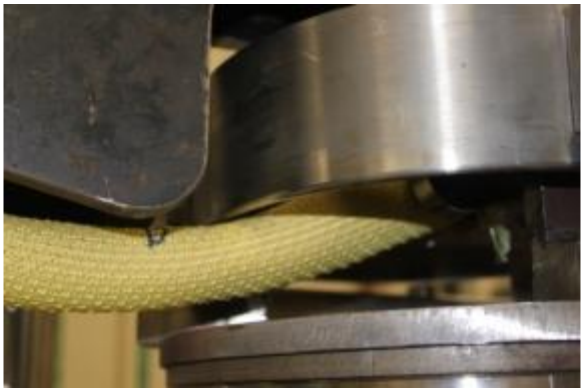

Photo 4. Protected riser and contact edge (close-up view).

Photo 5. Protected riser under load.

Photo 6. Protected riser under load (close-up view).

C. Test Procedure

Testing proceeded similarly to the abrasion testing performed in [1]. In the current test series, the cover to be evaluated was first installed on the riser sample and adjusted to ensure each layer was centered on the riser. The protected riser sample was then routed through the lower fixture and secured to the upper fixture using 0.75-inch diameter smooth pins (Photo 1). The upper and lower fixtures were then brought together, allowing the riser to be installed in the fixture (Photo 3 and Photo 4). The lever arm was used to rotate the turn-table to position the riser at one end of the contact area. The upper and lower fixtures were then separated to achieve and maintain the desired normal force of 17,600 lbs. Once the desired normal force was achieved, the lever arm was used to rotate the turn-table in order to translate the riser along the contact edge (Photo 5). This completed the first abrasive pass.

As previously noted, the abrasion distance available during a single pass was limited to approximately 6 inches, requiring two passes to achieve the required abrasion distance of 12 inches. This was achieved by unloading the riser after the first pass, resetting the contact edge to the initial position, loading the riser against the contact edge, and then abrading again in the same direction.

Finally, the system was unloaded and the riser sample removed for inspection. Following inspection, the riser cover design was adjusted to optimize abrasion protection. The first cover design to completely protect the riser from abrasive damage was subjected to two separate over-test conditions. The first combined a 20,000 lb normal load with the standard abrasion distance of 12 inches. The second combined the standard normal load of 17,600 lb with an abrasion distance of 18 inches. The covers used in these over-test conditions were inspected for damage and used to determine the viability of the design as a candidate protective solution.

Once a design candidate was selected, the riser loops used during testing of the design candidate were tensioned to failure. Each loop was carefully positioned to place the section of the line with potential damage midway between the load-bearing pins (Photo 7). The measured loads were used to calculate the strength reduction resulting from abrasive contact. This knockdown factor is the ratio of the strength of the damaged loop to the average strength of the undamaged control loops.

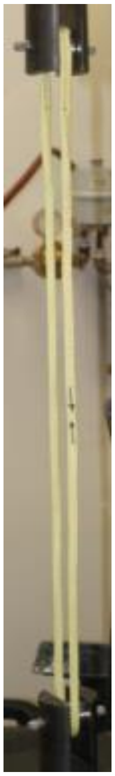

Photo 7. Riser loop tensile test setup.

D. Abrasion Test Results

Testing was completed successfully. The iterative nature of testing led to a variety of cover designs, as described in Table 3.

Table 3. Initial Testing - Cover Design and Test Observations.

#	Inner Kevlar Sleeve	Middle Sleeve	Outer (Rolling) Sleeve	Rotational Constraints	Results
A	Teflon subsleeves (each Kevlar® line individually sleeved)	Loose Spectra	Tubular Kevlar®	Middle and Outer layers hand-tacked together	Observations: Test load achieved 17,600 lbs, sleeve rolled well Sleeve damage: Tubular Kevlar® undamaged, Spectra melted & tore, teflon subsleeves (9 of 24) torn Line damage: No apparent damage
B	Teflon (tight)	Teflon (loose)	Tubular Kevlar®	Middle and Outer layers hand-tacked together	Observations: Rolling cover initially stuck, then rolled well Sleeve damage: Tubular Kevlar® undamaged, loose Teflon severed, tight Teflon torn Line damage: Some riser strands broken
C	Spectra (tight)	Teflon 1.5” (snug)	Tubular Kevlar®	None	Observations: Outer cover initially stuck, then rolled well Sleeve damage: Tubular Kevlar® undamaged, Teflon tore, Spectra melted Line damage: Minor damage to some, one line nearly severed
D	Spectra (tight)	Teflon 1.75”	Tubular Kevlar®	Middle and Outer layers hand-tacked together	Observations: Outer cover initially stuck, then rolled well Sleeve damage: Tubular Kevlar® undamaged, teflon tear was nearly circumferential, spectra melted Line damage: No apparent damage, creases & shiny spots visible
E	10-oz Kevlar® (tight)	Teflon 1.75”	Tubular Kevlar®	Middle and Outer layers taped together to shorten length and increase diameter of Outer Kevlar sleeve	Observations: Outer cover initially stuck, then rolled well Sleeve damage: Tubular Kevlar® undamaged, Teflon tore, 10-oz Kevlar® had slight damage Line damage: Creased, no apparent damage
F	10-oz Kevlar® with outer Teflon layer (tight)	Teflon 1.75”	Tubular Kevlar®	Middle and Outer layers taped together	Observations: Outer cover initially stuck, then rolled well Sleeve damage: Tubular Kevlar® undamaged, middle Teflon cut in half, inner Teflon cut, 10-oz Kevlar® had a hole in it Line damage: One cord damaged
G	Tubular Kevlar®	None	Tubular Kevlar®	None	Observations: Strongly resistant to rolling, eventually slid, could not slide 6 inches during first pass, rolled/slid 6 inches on second pass Sleeve damage: Outer undamaged, inner cut Line damage: No apparent damage, creases & shiny spots visible
H	Tubular Kevlar®	Teflon 1.75”	Tubular Kevlar®	None	Observations: Outer cover initially stuck, then rolled well Sleeve damage: Outer undamaged, Teflon severed, inner cut Line damage: Minimal damage to lines: one broken yarn, shiny creases
I	10-oz Kevlar® (tight)	Teflon 1.75”	Tubular Kevlar®	None	Observations: Outer cover initially stuck, then rolled well Sleeve damage: Tubular Kevlar® undamaged, Teflon tore, 10-oz Kevlar® had slight damage Line damage: Creased, no apparent damage
J	10-oz Kevlar® (tight)	Teflon 1.75” (2 layers)	Tubular Kevlar®	None	Observations: Outer cover initially stuck, then rolled well Sleeve damage: Tubular Kevlar® undamaged, outer Teflon cut in half, inner Teflon tore, 10-oz Kevlar® had slight damage Line damage: No apparent damage
K	10-oz Kevlar® (tight)	Teflon 1.75” (5.5 wraps)	Tubular Kevlar®	None	Observations: Outer cover initially stuck, then rolled well Sleeve damage: Tubular Kevlar® undamaged, cut all layers of Teflon (didn’t roll), 10-oz Kevlar® had slight damage Line damage: No apparent damage
L	10-oz Kevlar® (tight) (2 wraps)	Teflon 1.75”	Tubular Kevlar®	Middle layer taped to Inner layer	Observations: Excellent performance Sleeve damage: Minor damage to Tubular Kevlar®, Teflon cut, no damage to inner layer Line damage: No apparent damage, no shiny creases

#	Inner Kevlar Sleeve	Middle Sleeve	Outer (Rolling) Sleeve	Rotational Constraints	Results
M	10-oz Kevlar® (tight) (2 wraps)	Teflon 1.75”	Tubular Kevlar®	Middle layer taped to Inner layer	Observations: Over-stress of L design @ 20klbs & 18 inches (3 strokes) Sleeve damage: Minor damage to Tubular Kevlar®, Teflon cut, 10-oz Kevlar® damaged (both layers) Line damage: Slight damage to 3 lines
N	10-oz Kevlar® (tight) (2 wraps)	Teflon 1.75”	Tubular Kevlar®	Middle layer taped to Inner layer	Observations: Over-stress of L design @ 17600 lbs & 18 inches (3 strokes) Sleeve damage: Tubular Kevlar® undamaged, Teflon cut in half, 10-oz Kevlar® had slight damage Line damage: No apparent damage, shiny creases

Based on these test results, cover design “L” demonstrated the most effective abrasion protection and was selected for knockdown factor evaluation. Design “N” was an over-test of “L” and was also selected for comparison. Observable effects of abrasion on designs “L” and “N” are shown on Photo 8 through Photo 13.

Photo 8. Post-test exterior, “L”.

Photo 9. Post-test exterior, “N”.

Photo 10. Post-test inner Kevlar sleeve, “L”.

Photo 11. Post-test inner Kevlar sleeve, “N”.

Photo 12. Post-test lines, “L”.

Photo 13. Post-test lines, “N”.

E. Tensile Test Results

Each individual loop of the L and N riser samples was then tensioned to failure using an Instron 5884 with 1.375-inch diameter polished bushings on the 0.5-inch diameter pins in order to match the flight pin diameter. Each loop was marked prior to testing to identify the abrasion point (see the arrows on Photo 14). The failure modes for all the samples included bushing break (BB), end of insertion break (IB), and damage break (DB). Typical results of a failure at the end of the inserted line (IB) are shown on Photo 14. Maximum tensile strength data and failure mode for each sample are shown in Table 4. Nine unabraded control samples were tested for comparison.

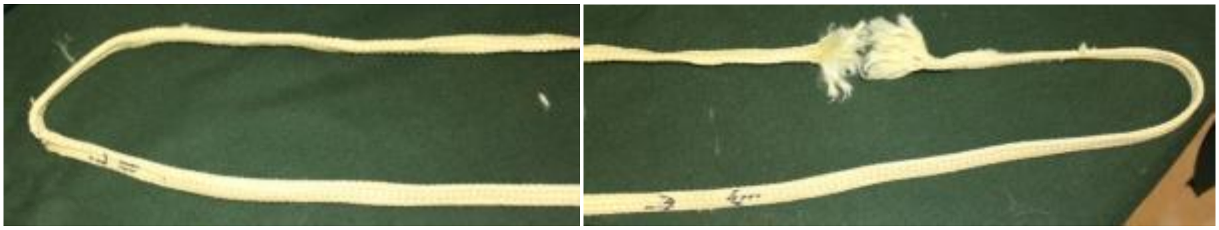

Photo 14. Typical tensile testing results.

Table 4. Initial Testing - Riser Sample Break Test Results.

Sample	Control	Break Location	L (Selected Design)	Break Location	N (Overtest of Selected Design)	Break Location
	lb		lb		lb	
1	12688	IB	10770	IB	12695	IB
2	12164	BB	12312	BB	11900	BB
3	11999	IB	10970	DB	11089	DB
4	10988	IB	10603	IB	11095	IB
5	10568	IB	11984	IB	9937	IB
6	11336	IB	10753	DB	11854	IB
7	11116	IB	11750	IB	12665	IB
8	11769	IB	12004	DB	10938	IB
9	9881	IB	11371	IB	7731	DB
10	-	-	11979	IB	12558	IB
11	-	-	10745	FD	10616	IB
12	-	-	12457	BB	11262	IB
Average	11390		11475		11195	
Standard Deviation (n-1)	865		682		1389	

* Sum of the samples multiplied by 12/9 to provide total strength comparable to samples L and N
BB Bushing Break
IB Insertion Break
DB Damage Break
FD Possible Fixture Damage

The average strength of the control samples was 11390 lbs, whereas the average strength of "L" samples was 11475 lbs, indicating the sleeves adequately protected the risers from abrasion.

F. Conclusion of China Lake Preliminary Testing

The success of design "L" led to its selection as the baseline design for full-scale abrasion testing at JSC's Structural Test Lab.

IV. Evaluation Testing at JSC

The overall procedure involved abrading a given protected riser sample against a variety of edge radii and corresponding bend angles and contact loads. The riser samples were then tensioned to failure and the measured peak strength compared to the peak strength of undamaged control samples.

A. Test Materials

1. Riser Samples

A total of ten riser samples were fabricated for evaluation testing at JSC. Each riser was 17 ft long and composed of 12 continuous loops of 5000-lb Kevlar® rope. Each loop was numbered and labeled to aid assembly. One riser was set aside as a control. An example riser is shown on Photo 15.

Photo 15. CPAS drogue riser sample.

2. Cover Materials

Cover materials used in design "L" were used to fabricate covers for each test sample (see Table 2 and Table 3 on pages 4 and 6 respectively). The 10-oz plain weave Kevlar cloth was used as the inner Kevlar sleeve, the Teflon cloth was used as the lubricating middle sleeve, and the 10,000-lb Kevlar tubing was used as the rolling outer Kevlar sleeve for each test.

3. Contact Edge Radii

Four contact edges were fabricated from 7075-T7375 aluminum for CPAS drogue riser abrasion testing, two of which have direct analogues to flight contact surfaces. These include the Drogue Fair Lead (5/8-inch edge radius, [4]) and the LAS R&R Bracket (1/4" edge radius, [5]). The other two edge radii (3/8-inch and 1/8-inch) were included as oversize and undersize LAS R&R Bracket analogues. Though the flight Drogue Fair Lead and LAS R&R are made from titanium, the difference in friction coefficients of Kevlar against titanium versus aluminum at low temperatures was assumed to be negligible. An additional edge, representing the sharp edge of the drogue mortar, was not available to test as the drogue mortar was being redesigned at the time these tests were conducted. As this edge may represent the worst case, additional testing on this edge is highly recommended when available. The edge radii available for testing are summarized in Table 5.

Table 5. Edge radii.

Contact Surface Analogue	Edge Radius (in)	Bend Angle	Maximum Contact Load (lb)
Drogue Fair Lead	5/8	90º	42,000
LAS R&R Bracket (oversize)	3/8	60º	17,600
LAS R&R Bracket	1/4	60º	17,600
LAS R&R Bracket (undersize)	1/8	60º	17,600

B. Test Setup

1. Riser Sample Preparation

Each riser sample was laid out on the assembly table atop the inner Kevlar sleeve cloth, as shown on Photo 16. The 10-oz plain-weave Kevlar cloth of the inner Kevlar sleeve was measured and cut to a width sufficient to wrap twice about the riser sample, thus forming two protective layers, as shown on Photo 17. The inner sleeve was sized to be evenly snug along its length. The inner Kevlar sleeve was then secured with Teflon tape, as shown on Photo 18. The Teflon cloth of the middle sleeve was cut to be slightly shorter than the inner Kevlar sleeve, wrapped about the inner Kevlar sleeve to form a single lubricating layer, and secured with Teflon tape, as shown by Photo 19. The Teflon sleeve was also sized to be evenly snug along its length. The sleeved riser sample was then inserted into the outer Kevlar sleeve, as shown on Photo 20. The inner Kevlar sleeve was taped to the riser and the Teflon sleeve taped to the inner sleeve on each end, with the outer sleeve left untaped to allow it to roll. The final assembly of the protected riser sample is shown on Photo 21 and its flexibility is demonstrated on Photo 22.


Photo 16. Riser sample about to be wrapped in Kevlar cloth.


Photo 17. Riser sample being wrapped in Kevlar.


Photo 18. Kevlar cloth inner sleeve secured with Teflon tape.


Photo 19. Teflon middle sleeve secured with Teflon tape.

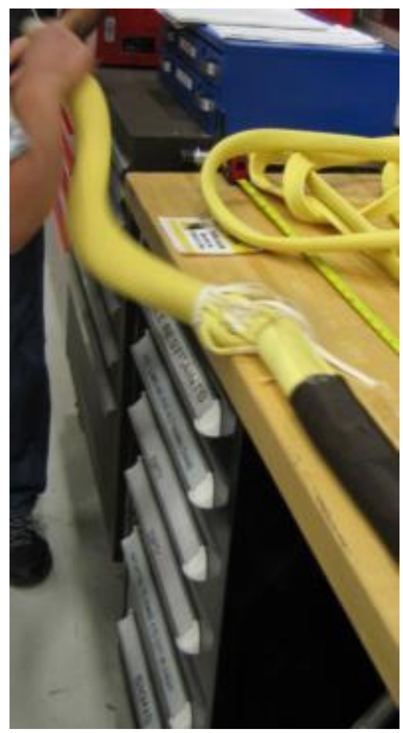
Photo 20. Riser sample being inserted into tubular Kevlar outer sleeve.

Photo 21. Riser sample with protective textile cover.

2. Test Fixture

Two hardware interface "knuckles" were used to connect the riser sample to the test fixture. The knuckle used to simulate attachment to the capsule is shown on Photo 23, whereas the knuckle used to simulate the parachute load is shown on Photo 24. The riser sample was first attached to the capsule knuckle and installed in the abrasion fixture, as shown on Photo 25. The far end of the riser was then fed through the edge radius tube, as shown on Photo 26 and Photo 28. The riser cover was marked to provide visual indication of rotation. Finally, the far end of the riser sample was routed through safety ties, as shown on Photo 27 and attached to the parachute knuckle, load cell, and hydraulic ram assembly, as shown on Photo 29.

Photo 22. Flexibility demonstration of protected CPAS drogue textile riser.

Photo 23. Riser sample with hardware interface "knuckle" attached (abrasion fixture end).

Photo 24. Riser sample with hardware interface "knuckle" attached (tensioned end).

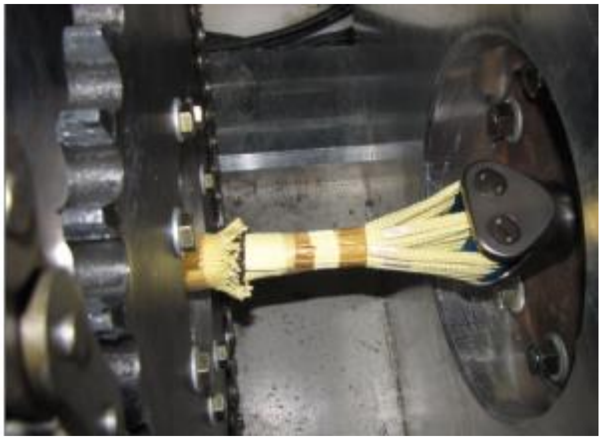

Photo 25. Riser sample attached to abrasion fixture.

Photo 26. Riser sample passing through edge radius tube.

Photo 28. Riser sample in contact with 5/8" edge radius (Fair Lead analogue) and marked to provide visual indication of rotation.

Photo 27. Riser sample at 90º bend angle (Fair Lead analogue).

Photo 29. Hydraulic ram and load cell attachment.

A limitation of the test fixture was the relative motion between contact edge radius and the knuckle. Rotation of these items will be coupled in the flight configuration.

C. Abrasion Test Procedure

Two types of abrasion tests were performed during this test series, depending on the condition being simulated. Each test was conducted to replicate abrasion testing previously performed on steel cable risers.

The test matrix is included in Table 6. The majority of the test assets were allocated to evaluate the performance of the textile riser cover in contact with the Drogue Fair Lead, as it involved the most likely scenario as well as the largest contact load and longest abrasion distance.

Table 6. JSC test matrix.

# Tests	Contact Surface Analogue	Edge Radius (in)	Bend Angle	Maximum Contact Load (lb)	Abrasion Distance at Max Load (in)
6	Drogue Fair Lead	5/8	90º	42,000	60
1	LAS R&R Bracket (oversize)	3/8	60º	17,600	12
1	LAS R&R Bracket	1/4	60º	17,600	12
TBD*	LAS R&R Bracket (undersize)	1/8	60º	17,600	12

*Additional testing to be performed as time and material availability permit.

The command profile used to evaluate abrasion between the Drogue riser and the Fair Lead edge radius is shown in Table 7. Drogue Fair Lead testing involved tensioning the riser sample to the peak load of 42,000 lbs, then ramping down to the steady-state load of 11,330 lbs for 51 seconds. The profile was derived to simulate drogue inflation loads followed by abrasion under steady-state conditions.

Test 1 used the steel cable command profile, but failed to reach the peak load due to the limited stroke of the hydraulic actualtor. Analysis of the command/response of the system revealed a total system lag of 3.17 seconds. The load ramp time (Step 4) was therefore increased by six seconds to ensure achievement of peak load. The hold time (Step 5) was consequently reduced by six seconds in order to match the load profile and total abrasion distance experienced by the steel cable.

Table 7. Fair Lead command profile, tests 2 through 6.

Step	Duration (s)	Load (lb)	Rate of Fixture Rotation (RPM)	Note
1	2	0	0	Initial systems check.
2	5	0	0 => 100	Rotator check.
3	5.28	=> 43735	100	Ramp to peak load.
4	7	43735	100	Additional ramp to peak load with 1s hold time. Duration increased from 1s to match load profile of steel cable for equivalent comparison. Simulates initial contact of full-open parachute load.
5	12.02	=> 11330	100	Ramp to steady-state load. Reduced from 18.02s for steel cable to match load profile for equivalent comparison.
6	1	11330	100 => 134	Ramp to steady-state rotational rate.
7	51	11330	134	Steady-state rotational rate and load. Simulates steady state parachute load during descent.
8	6.61	=> 0	134	Ramp to unload condition.
9	1	0	134 => 0	Stop rotation.

A separate profile was used to evaluate abrasion between the drogue riser and the LAS R&R edge radii, as shown in Table 8. The different profiles were designed to simulate the different abrasion conditions of the Fair Lead and LAS R&R.

Table 8. LAS R&R command profile, tests 7 through 10.

Step	Duration (s)	Load (lb)	Rate of Fixture Rotation (RPM)	Note
1	Manual	0	0	Initial systems check.
2	Manual	=> 500	0	Pre-tension sample.
3	2.2	=> 17600	=> 10	Ramp load and rotation rate.
4	5	17600	10	Steady-state rotational rate and load.
5	1	=> 0	=> 0	Ramp unload and stop rotation.

Material lengths were initially standardized to provide a consistent evaluation of the textile riser cover. Once initial testing was completed with Test 8, the cover was subjected to increasingly adverse configurations in an attempt to fail the cover. The final tests were conducted with the cover fully spiraled prior to the test to prevent rolling motion and force the cover to slide on the edge radius analogue. This constrained configuration allowed the sleeve lengths to be significantly shortened.

Table 9. Test sample configurations.

Test	Edge Radius	Target Peak Load (lb)	Outer Kevlar sleeve Length (in)	Middle Sleeve Length (in)	Middle Sleeve Width (in)	Inner Kevlar sleeve Length (in)	Inner Kevlar sleeve Width (in)
1	5/8"	42000	80	42	6	50	10
2	5/8"	42000	24	18	6	50	10
3	5/8"	42000	80	42	6	50	10
4	5/8"	42000	80	42	6	50	10
5	5/8"	42000	80	42	6	50	10
6	5/8"	42000	80	42	6	50	10
7	3/8"	17600	31.5	Greater than outer	6	Greater than middle	10
8	1/8"	17600	No Data	No Data	6	No Data	10
9	1/8"	17600	14	Greater than outer	6	Greater than middle	10
10	1/8"	17600	8	10	6	12	10
11	1/8"	17600	14	6	6	38	10

D. Abrasion Test Results

1. Test 1 – Drogue Fair Lead (5/8-inch radius, 90º bend angle, 42,000 lb target peak contact load)

The initial setup is shown on Photo 30. This test used the original command profile used during testing of the steel cable. The outer cover rotated during the test until it was bound, at which time the cover began sliding on the edge radius. The resulting spiral is shown on Photo 31, Photo 32, and Photo 33.

The outer Kevlar sleeve and middle Teflon sleeves were torn, as shown on Photo 34 and Photo 35, respectively. The inner Kevlar sleeve, however, exhibited only a shiny spot and no visible damage, as shown on Photo 36. The lines were similarly devoid of visible damage, as shown on Photo 37.

As previously mentioned, Test 1 failed to achieve the desired peak load of 42,000 lbs. The load instead peaked at 37,000 lbs. The command inputs and system response was used to determine an overall system response time of 3.17 seconds, allowing subsequent tests to achieve the desired load. As the peak load was not achieved, damage due to abrasive contact was consequently reduced and was not used to evaluate the knockdown factor due to abrasion.

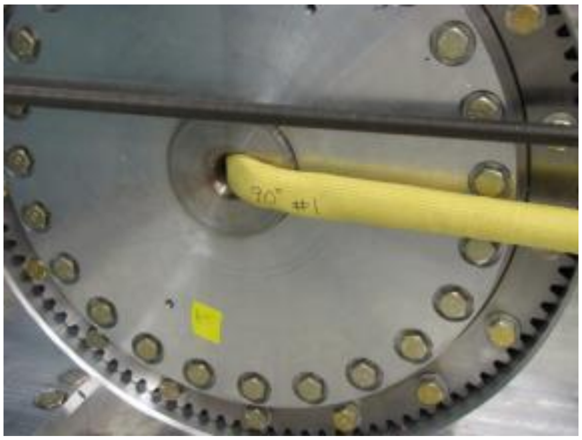

Photo 30. Test 1 before testing.

Photo 31. Test 1 post-test.

Photo 32. Test 1 post-test (close-up).

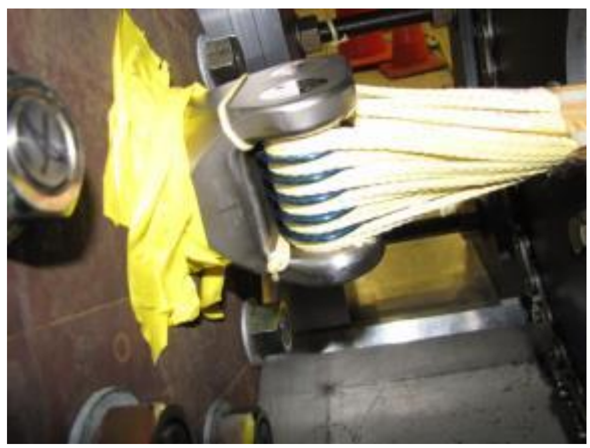

Photo 33. Test 1 post-test (knuckle).

Photo 34. Test 1 effects (outer Kevlar sleeve).

Photo 35. Test 1 effects (Teflon sleeve).

Photo 36. Test 1 effects (inner Kevlar sleeve).

Photo 37. Test 1 effects (lines).

2. Test 2 – Drogue Fair Lead (5/8-inch radius, 90º bend angle, 42,000 lb target peak contact load)

Test 2 was prepared with a short (24") outer cover to preserve the limited amount of cover material. It was also the first to employ the modified command profile. The test achieved a peak load of 42,700 lbs, meeting the 42,000 lb requirement.

The effect of abrasion on the riser cover was different from Test 1. The outer cover rotated during abrasive contact loading, but did not tear the outer Kevlar sleeve, as shown on Photo 38, Photo 39, Photo 40, Photo 41, and Photo 42. The middle Teflon sleeve was torn, as shown on Photo 43. The inner Kevlar sleeve and lines were compressed and shiny, but had no visible damage, as shown on Photo 44 and Photo 45.

Photo 38. Test 2 before testing.

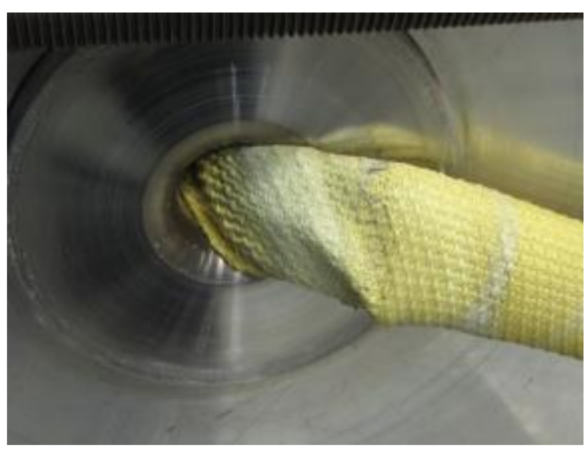

Photo 39. Test 2 post-test (close-up A).

Photo 40. Test 2 post-test (close-up B).

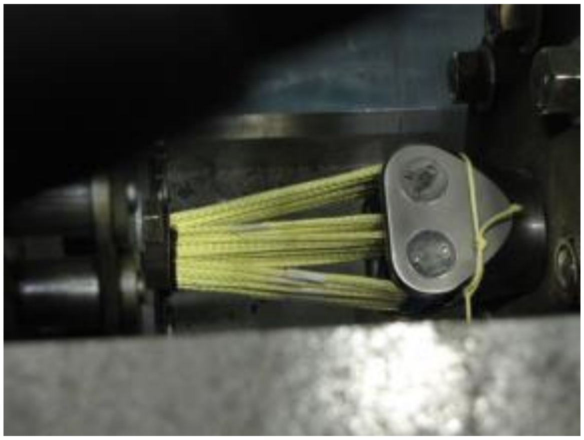

Photo 41. Test 2 post-test (knuckle).

Photo 42. Test 2 effects (outer Kevlar sleeve).

Photo 43. Test 2 effects (Teflon sleeve).

Photo 44. Test 2 effects (inner Kevlar sleeve).

Photo 45. Test 2 effects (lines).

3. Test 3 – Drogue Fair Lead (5/8-inch radius, 90º bend angle, 42,000 lb target peak contact load)

For Test 3, the outer sleeve was taped to the Teflon sleeve so all three sleeves were taped together to prevent rolling and the outer sleeve was pulled snug to the riser. As the outer sleeve was designed to roll to minimize the cutting action of sliding friction, this and subsequent tests were designed to prevent the sleeve from rolling to explore the limits of its ability to protect the risers from abrasion.

The peak load was observed to be 42,600 lbs and damage to the protective sleeving appeared very similar to Test 2. The riser cover did not rotate during testing and damage to the outer Kevlar sleeve was limited to minor holes. The Teflon middle sleeve was torn, as usual. The inner Kevlar sleeve showed Teflon residue, but no damage. The lines showed slightly shiny spots, but no visible damage.

4. *Test 4 – Drogue Fair Lead (5/8-inch radius, 90º bend angle, 42,000 lb target peak contact load)*

Test 4 was conducted in the same manner as Test 3, with similar results. The peak load was observed to be 42,800 lbs. The outer Kevlar sleeve did not rotate and had minor holes. The Teflon middle sleeve was torn, as usual. The inner Kevlar sleeve showed Teflon residue, but no damage. Line 7 was folded where the inner cover seam mashed it (Photo 46).

Photo 46. Test 4 effects (lines).

5. *Test 5 – Drogue Fair Lead (5/8-inch radius, 90º bend angle, 42,000 lb target peak contact load)*

Test 5 was conducted in the same manner as Test 3, with the outer Kevlar sleeve taped directly to the riser (Photo 47) to help limit rotation.

The peak load was observed to be 42,800 lbs. The outer Kevlar sleeve was buffed smooth by the sliding motion and had no visible damage. The Teflon middle sleeve experienced a very slight tear. The inner Kevlar sleeve showed no Teflon residue or damage. The lines exhibited a nearly undetectable sheen.

Photo 47. Test 5 taped outer sleeves.

6. *Test 6 – Drogue Fair Lead (5/8-inch radius, 90º bend angle, 42,000 lb target peak contact load)*

Test 6 was conducted in the same manner as Test 5, including the taped outer sleeve.

The peak load was observed to be 42,900 lbs. The outer Kevlar sleeve experienced a ¾” diameter hole. The Teflon middle sleeve experienced a 1” diameter hole. The inner Kevlar sleeve showed some Teflon residue, but no damage. The lines had slightly shiny areas, but no visible damage.

7. *Test 7 – LAS R&R Analogue (3/8-inch radius, 60º bend angle, 17,600 lb target peak contact load)*

Test 7 was the first test of the LAS R&R edge radius analogues. The test setup was adjusted to match the LAS R&R 3/8-inch analogue contact radius (Photo 48). The sleeve lengths were reduced to conserve limited cover materials. The inner sleeve was taped at both ends and the middle and outer sleeves at the far end were also taped to prevent rolling (Photo 49). The middle and outer sleeves inside the fair lead were not taped to more accurately simulate contact away from the riser knuckle.

The contact radius completed 1.75 rotations. A peak load of 18,200 lbs was sustained for 14 seconds.

The Kevlar outer sleeve rotated about a quarter turn and then slid. It appeared to receive some aluminum residue from the contact radius (Photo 50). The Teflon middle sleeve was torn about half the way around the sleeve (Photo 51). The Kevlar inner sleeve displayed some Teflon transfer, but had no visible damage (Photo 52). The lines likewise had slightly shiny areas, but no visible damage (Photo 53).

Photo 48. Test 7 (LAS R&R) setup (bend angle).

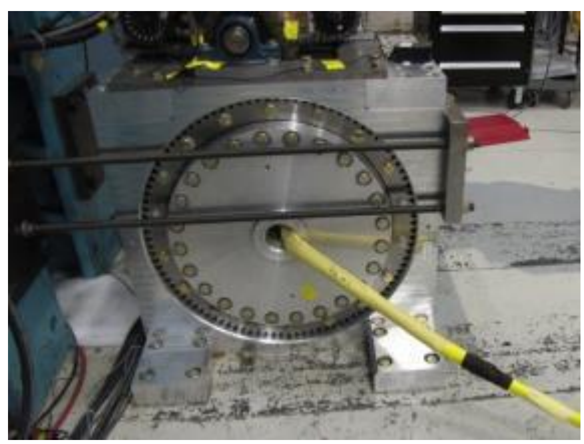

Photo 49. Test 7 setup (taped sleeves).

Photo 50. Test 7 results (outer sleeve).

Photo 51. Test 7 results (middle sleeve).

Photo 52. Test 7 results (inner sleeve).

Photo 53. Test 7 results (lines).

8. Test 8 – LAS R&R Analogue (1/8-inch radius, 60º bend angle, 17,600 lb target peak contact load)

Test 8 was similar to Test 7, except with a 1/8-inch radius LAS R&R analogue (Photo 54). The 1/4" radius was not tested in order to optimize the usage of limited cover materials.

The target load was met or exceeded for 8.7 seconds, with an overall peak load of 18,672 lbs.

The Kevlar outer sleeve twisted at least one complete rotation (Photo 55) and retained some Aluminum residue from the contact radius, but was otherwise undamaged (Photo 56). The middle sleeve was torn (Photo 57) and transferred Teflon residue to the inner sleeve (Photo 58); the inner sleeve was buffed but undamaged. The lines were also slightly shiny and undamaged (Photo 59).

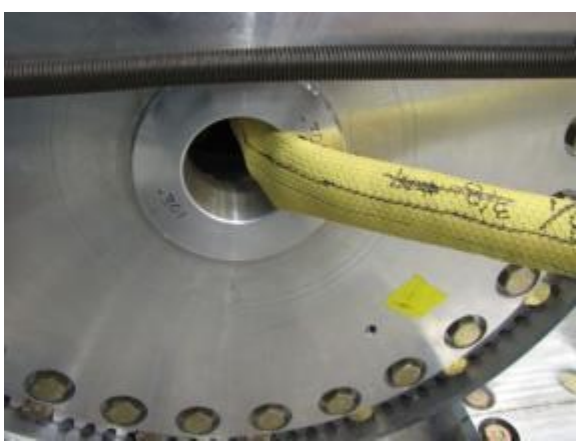

Photo 54. Test 8 setup (LAS R&R 1/8").

Photo 55. Test 8 results (twist).

Photo 56. Test 8 results (outer sleeve).

Photo 57. Test 8 results (middle sleeve).

Photo 58. Test 8 results (inner sleeve).

Photo 59. Test 8 results (lines).

9. Test 9 – LAS R&R Analogue (1/8-inch radius, 60º bend angle, 17,600 lb target peak contact load)

Test 9 repeated the method used by Test 8. In addition, the outer sleeve was taped 10” from the edge inside the fixture and 20” outside the fixture to simulate 14” maximum roll length of this diameter cover material.

The target load was met or exceeded for 9.4 seconds, with an overall peak load of 18,716 lbs.

The Kevlar outer sleeve completed one revolution due to extra material inside the fixture, resulting in more sleeve rotation than Test 8. The middle Teflon sleeve was completely severed. The Kevlar inner sleeve had Teflon residue and no damage. The lines were slightly shiny.

10. Test 10 – LAS R&R Analogue (1/8-inch radius, 60º bend angle, 17,600 lb target peak contact load)

Test 10 was an over-test of the protective cover based on the method used during Test 9. In addition, the sleeves were all taped tight to prevent rotation and maximize cutting rotation. The intent was to simulate a worst-case scenario where the cover could not rotate and would experience only sliding, abrasive cutting motion, hence the nickname “Bandsaw Test #1”. Note: Test 10 reused the lines from Test 1. The Test 1 contact area was marked and the lines were rotated around the attachment pins to position the Test 1 contact area midway between the attachment pins in order to separate the Test 1 and Test 10 contact areas.

The target load was met or exceeded for 9.2 seconds, with an overall peak load of 18,765 lbs.

The Kevlar outer sleeve sheared out from under the tape, allowing it to roll completely. The Teflon middle sleeve was cut half way through. The Kevlar inner sleeve had Teflon residue and no damage. The lines were slightly shiny.

11. Test 11 – LAS R&R Analogue (1/8-inch radius, 60º bend angle, 17,600 lb target peak contact load)

Test 11 repeated the method used by Test 10. In addition, the Kevlar outer sleeve was spiraled and milked down onto the riser as tightly as was possible by hand and then taped tightly and the Teflon middle sleeve was shortened to the minimum necessary in the contact region. As in Test 10, Test 11 was intended to maximize cutting motion. Also as in Test 10, Test 11 used the lines from Test 1, which were rotated again about the attachment pins to separate the contact areas.

The target load was met or exceeded for 9.3 seconds, with an overall peak load of 18,701 lbs.

The Kevlar outer sleeve only rotated about 3/8-inch and experienced a 3/4" cut. The Teflon middle sleeve was cut halfway through. The Kevlar inner sleeve had Teflon residue and no damage. The lines were slightly shiny.

Photo 60. Test 11 setup (Short Teflon middle sleeve).

Photo 61. Test 11 setup (pre-twist).

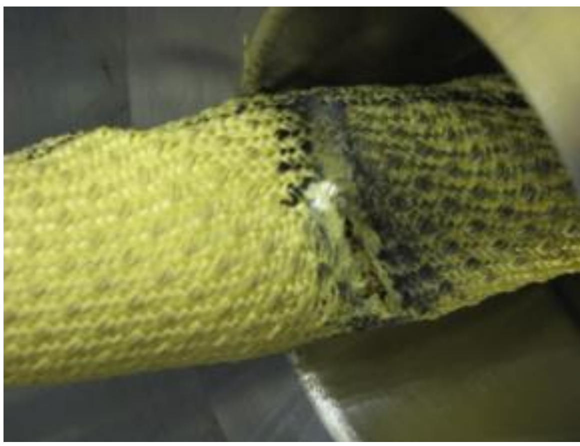

Photo 62. Test 11 results (outer sleeve).

Photo 63. Test 11 results (middle sleeve).

Photo 64. Test 11 results (inner sleeve).

Photo 65. Test 11 results (lines).

12. Abrasion Testing Summary

Testing conducted at JSC's Structural Test Lab demonstrated the ability of a textile riser cover to protect against abrasive contact analogous to the maximum contact load and duration predicted for drogue riser contact with the Drogue Fair Lead and LAS R&R bracket. Observations indicated abrasive contact would cause a visual effect, described as a "slight shininess" of the material in the contact area. Test notes are summarized in Table 10. Tensile testing was subsequently performed to quantitatively detect and define any resulting reduction in strength.

Table 10. Summary of drogue riser abrasion test notes.

Test	Edge Radius	Peak Load (lb)	Outer Kevlar sleeve	Middle Sleeve Notes	Inner Kevlar sleeve Notes	Lines Notes	Other Notes
1	5/8"	37,000	Rotated until becoming bound, folded and tore through in small area. Spiraled toward fairlead on inside due to spreading internal lines.	Ripped.	Shiny spot, no damage.	Slightly shiny areas, but no visible damage.	Failed to reach target peak load.
2	5/8"	42,700	Rotated during high load, then slowed down (neve full speed roll). Spiraled toward fairlead, no visible damage.	Torn.	Teflon residue, no damage.	Slightly shiny spots, but no visible damage.	Target peak load achieved.
3	5/8"	42,600	No sleeve rotation, minor holes.	Torn.	Teflon residue, no damage.	Slightly shiny spots, but no visible damage.	-
4	5/8"	42,800	No sleeve rotation, minor holes.	Torn.	Teflon residue, no damage.	Line 7 was folded where extra inner cover mashed it.	-
5	5/8"	42,800	Outer cover no tears (buffed smooth)	Very slight tear.	No teflon transfer or damage.	Very light shinyness, virtually nonexistent.	-
6	5/8"	42,900	Outer cover had 3/4" hole	Teflon had 1" hole	Some teflon transfer, no damage.	Very light shinyness, virtually nonexistent.	-
7	3/8"	18,200	Aluminum transfer on outer cover, rotated about 1/4 turn	Teflon torn about half circumference.	Some teflon transfer, no damage.	Slightly shiny areas, but no visible damage.	Rotated 1.75 revolutions. Peak load of 18.2k for 14 seconds
8	1/8"	18,762	N/R	N/R	N/R	N/R	Similar to Test 7
9	1/8"	18,716	Outer rolled complete revolution due to extra material inside fixture, resulting in more rotation than Sample 8	Teflon severed	Teflon residue	Slight shinyness	-
10	1/8"	18,765	Came untaped and rolled completely	Teflon cut half way through	Teflon residue	Slight shinyness	“Bandsaw” test #1
11	1/8"	18,701	3/4" cut on outer Kevlar sleeve	Teflon cut half way through	Teflon residue	Slight shinyness	“Bandsaw” test #2; Rotated about 3/8 inch

N/R Not Recorded.

E. Tensile Testing

Tensile test results were originally presented in [6].

1. Test Procedure & Equipment

In addition to the twelve abraded riser loops composing each of the nine riser samples, a set of seven untested loops was subjected to tensile testing as a control. The number of control loops was limited by available materials. Each loop was attached to two 1-3/8-inch pins (Photo 66) and individually loaded to failure. No damage was observed in the abraded areas prior to testing other than the “shininess” seen immediately after abrasion testing.

Photo 66. Tensile test fixture (1-3/8” pin).

Photo 67. Drogue Knuckle Spool.

2. Test Results

Tensile test results are tabulated in Table 11. Test data indicate the abraded samples as a group demonstrated a lower strength than the control group. Only 2% of the samples, however, broke in the abraded area. One reason for this is the abrasion samples experienced a significant preload during the abrasion testing (the 5/8-inch radius more so than the 3/8-inch and 1/8-inch radius samples), while the control samples had no preload. Additionally, during abrasive testing the samples were attached to drogue knuckle spools (Photo 67), which constrain the width of the cord and increase its thickness. The control samples were never attached to knuckle spools and were only pulled to failure using 1-3/8-inch diameter pins.

Sample 1 did not reach the target load during Test 1. It was therefore subjected to additional abrasion testing in Tests 10 and 11 to qualitatively identify abrasion damage effects due to rotationally constrained scenarios.

Table 11. Riser Sample Break Test Results.

#	Edge Radius (in)	Loop 1 (lbf)	Loop 2 (lbf)	Loop 3 (lbf)	Loop 4 (lbf)	Loop 5 (lbf)	Loop 6 (lbf)	Loop 7 (lbf)	Loop 8 (lbf)	Loop 9 (lbf)	Loop 10 (lbf)	Loop 11 (lbf)	Loop 12 (lbf)
C	**Control**	10,773	10,943	11,314	12,006	11,099	11,580	11,304	-	-	-	-	-
1	**5/8**	10,911	10,662	10,137	10,362	10,328	10,955	10,614	9,873	10,400	9,656	9,683	10,565
2	**5/8**	10,946	10,726	10,964	10,659	10,746	10,779	10,812	10,659	11,050	10,245	10,453	9,670
3	**5/8**	10,600	10,588	10,752	10,107	10,794	10,685	10,253	10,476	10,445	10,104	10,478	10,185
4	**5/8**	10,705	10,293	10,306	10,579	10,923	10,518	9,006	10,386	10,343	10,106	10,216	10,061
5	**5/8**	10,955	9,829	10,744	10,397	10,046	10,856	10,649	10,105	10,393	10,037	10,865	9,497
6	**5/8**	10,221	10,289	10,262	10,424	10,924	10,733	9,770	10,209	10,345	11,314	10,827	10,686
7	**3/8**	11,200	11,076	10,914	10,332	10,934	11,065	11,201	11,452	10,851	10,569	10,672	11,144
8	**1/8**	10,412	10,702	10,755	9,579	10,881	10,288	10,520	10,678	10,280	11,105	10,260	10,598
9	**1/8**	11,128	11,535	11,071	10,733	11,100	9,916	10,104	10,603	11,594	10,790	11,052	11,461

Red: Broke in abraded area
Green: Broke at pin
Blue: Broke outside pin & abraded area

Of the control samples, slightly less than half (43%) broke at the pin and the remainder (57%) broke away from the pin.

Of the abraded samples, the vast majority (71%) broke at the pin and the remainder (27%) broke somewhere other than the pin or the abraded area. Only two of the 96 abraded loops (2%) failed in the abraded area: Loop 10 of Riser 3 and Loop 7 of Riser 4. As previously mentioned, Riser 3 and Riser 4 were tested against the Fair Lead 5/8-inch edge. None of the “sharp edge” 3/8-inch or 1/8-inch samples failed in the abraded area. Interestingly enough, Sample 1, which was abraded during Tests 1, 10, and 11, did not break at any of the abraded locations.

3. Knockdown Calculation

As shown in Table 11, the average breaking strength of the 7 control loops was 11,288 lbs. The average breaking strength of the loops in samples 2, 5, 6, 7, 8, and 9, in which none of the loops broke at the point of abrasion, ranged from 10,364 lbs to 10,951 lbs. As none of these samples broke at the point of abrasion, the breaking strengths should have been very similar, unless the test samples were affected by additional variables not present in the control samples. The most likely such variable was found to be the abrasion testing load cycle. The average breaking strength of the samples loaded to 46,000 lbs ranged from 10,287 lbs to 10,642 lbs, whereas the the average breaking strength of the samples loaded to 17,600 lbs ranged from 10,505 lbs to 10,951 lbs. These data indicate the magnitude of the load cycle corresponds to a reduced breaking strength apart from abrasion. The unloaded control samples, however, did not experience the same load cycle and are therefore a poor comparison group for determining the knockdown caused by abrasion.

A more suitable method isolates the amount of knockdown due to abrasion alone:

1) Identify a riser with loops which broke at the point of abrasion
2) Calculate the average and standard deviation of the breaking strength of all loops in the riser identified in Step 1
3) Subtract the standard deviation from the average breaking strength, this is the **Reference Strength**
4) Define the loops which did not break at the point of abrasion as the control group
5) Calculate the average and standard deviation breaking strength of all loops in the control group
6) Subtract the standard deviation from the average breaking strength of the control group, this is the **Control Strength**
7) The strength ratio **Reference Strength : Control Strength** is the **Abrasion Efficiency**

This method accounts for the effect of abrasion on the riser by comparing the overall average riser loop strength against the average strength of those loops which were unaffected by abrasion.

The above method was applied to Risers 3 and 4, in each of which a single loop broke at the point of abrasion. The associated abrasion efficiency values of these samples were calculated to be 0.995 and 0.967, respectively, as shown in Table 12.

Table 12. Riser Sample Break Test Results.

			Sample Set				Control Group			
Test Riser	**Edge Radius (in)**	**Abrasion Peak Load (lbf)**	**Average Loop Strength (lbf)**	**Standard Deviation of Loop Strength (lbf)**	**Reference Strength: Average minus Standard Deviation (lbf)**	**Abrasion Break?**	**Average Strength of Non-abrasion Failed Loops (lbf)**	**Standard Deviation of Non-Abrasion Failed Loops (lbf)**	**Control Strength: Non-abrasion Average Strength minus Non-abrasion Standard Deviation (lbf)**	**Abrasion Efficiency**
Control	N/A	N/A	11,288	412.65	10,875	N/A	-	-	-	-
1	5/8	37,000	10,346	436.55	9,909	No	-	-	-	1.000
2	5/8	42,700	10,642	377.41	10,265	No	-	-	-	1.000
3	5/8	42,600	10,456	243.80	10,212	Yes	10,488	227.81	10,260	0.995
4	5/8	42,800	10,287	473.00	9,814	Yes	10,403	259.10	10,144	0.967
5	5/8	42,800	10,364	465.44	9,899	No	-	-	-	1.000
6	5/8	42,900	10,500	411.71	10,088	No	-	-	-	1.000
7	3/8	18,200	10,951	310.42	10,641	No	-	-	-	1.000
8	1/8	17,600+	10,505	389.10	10,116	No	-	-	-	1.000
9	1/8	17,600+	10,924	528.04	10,396	No	-	-	-	1.000

V. Conclusion

Preliminary testing [1] of subscale CPAS drogue riser samples and various textile riser cover designs at the Naval Air Warfare Center, Weapons Division in China Lake, CA successfully identified a baseline design candidate for feasibility evaluation. Full-scale feasibility testing subsequently conducted at the Johnson Space Center in Houston, TX successfully determined the ability of the baseline design candidate to protect the textile drogue riser against a variety of relevant abrasive environments.

Future testing of the drogue and main risers against the redesigned drogue mortar edge will still be necessary to determine whether the efficiency value generated thus far encompasses all abrasion cases. Additionally, future testing should subject control samples to the same preload and end-mounting configuration as the abraded samples in order to isolate the abrasion effects.

VI. Future Work

The authors recommend the CPAS team evaluate and refine textile cover design for additional crew module contact interactions for both CPAS drogue and main textile reisers. These surfaces include the fair lead for each riser, the drogue mortar cans (in both fired and unfired conditions), and the LAS R&R bracket. The authors also recommend the CPAS team evaluate the test method to better isolate abrasion effects by subjecting controls to the same pre-loading environment, without abrasion, to account for non-abrasion knockdown effects.

VII. References

[1] E. J. Hennings and M. L. Petersen, "Protection of a Textile Parachute Riser from Temperature and Abrasion Using a Textile Cover System," in *Aerodynamic Decelerator Systems Conference*, Dublin, Ireland, 2011.

[2] NASA Multi-Purpose Crew Vehicle Program Office, "Riser Abrasion Tiger Team (RATT) Requirements Finalization," NASA Multi-Purpose Crew Vehicle Program Office, Houston, TX, May 2013.

[3] DuPont, "DuPont Kevlar(R) Technical Guide," April 2000. [Online]. Available: http://www2.dupont.com/Kevlar/en_US/assets/downloads/KEVLAR_Technical_Guide.pdf. [Accessed 7 April 2011].

[4] H. Nguyen, *Drogue Fair Lead (Drawing No. SDH36152050-002),* Houston, TX: NASA Johnson, 2013.

[5] H. Nguyen, *Drogue [R&R Bracket] Insert (Drawing No. SEH36154243-002),* Houston, TX: NASA Johnson, 2013.

[6] B. Anderson, "Proposed Abrasion Factor Calculation Based on Textile Riser Abrasion Test Results," Multi-Purpose Crew Vehicle Program Office, Houston, TX, 2013.

[7] NASA Ames Research Center, *Drawing No. 42654,* 2010.

[8] Space Systems Company, *ORION-TPS-12-009,* 2012.

[9] Airborne Systems, *Kevlar(R) Riser Sample Drawing No.,* DATE.